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PILE FOUNDATIONS FOR LARGE TOWERS ON PERMAFROST

By L. A. Nees, Assoc. M. ASCE

STRUCTURAL DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

PILE FOUNDATIONS FOR LARGE TOWERS ON PERMAFROST

By L. A. Nees,[1] Assoc. M. ASCE

Synopsis

The strategic importance of the Arctic region and the lack of knowledge of engineering conditions in this area make this paper of general interest to the profession. Confronted with the design of tower bases on permafrost soil, it was found necessary to conduct a series of tests to derive values for the factors of design. These tests are described and compared with previous research.

The design finally selected for the tower base involved a system of steel beams and piles that spread the load from the tower leg through annular rings and spider beams to a series of 8-in. piles. The design of this system is described, and steps are given for the design of the heat diverting pad necessary to prevent melting of the permafrost and resultant loss of pile friction. The question of pile imbedment is also discussed briefly.

Introduction

The vast reservoir of natural resources in the Arctic and the militarily strategic importance of these regions make it inevitable that they will attract the attention of the engineer with ever-increasing interest. It is safe to say that the background of engineering knowledge on Arctic conditions, especially in the field of permafrost, is not sufficiently advanced to provide well-established theories and criteria for design—especially on important structures. Great strides are being made in the preparation of design standards by a number of agencies in the United States, Canada, and Great Britain. Until these are available, the designer must depend largely upon empirical methods and isolated experiences. It is hoped that this paper, by outlining a rational method of design for an important structure and by describing a few model pile tests, will help to plug the gap in engineering knowledge.

Note.—Written comments are invited for publication; the last discussion should be submitted by May 1, 1951.

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Experiences with large tower construction in the Arctic in 1947 made it seem desirable to reduce the use of concrete in the foundations to a minimum. The idea of using piling seemed excellent, provided a reasonable method of design could be assured and a reliable estimate could be made of the adhesion of the piles to the permafrost under uplift stresses. The question of heat transmission was recognized as being a very important variable in the general problem.

Test Program

Research and Development.—Work was started on the preparation and analysis of a typical design, and at the same time a study was made of available data on the adhesive force of freezing. This study indicated the need for additional information. Therefore a series of small-scale tests was run to determine the envelope of the values of bond stress developed between steel piles and permafrost.

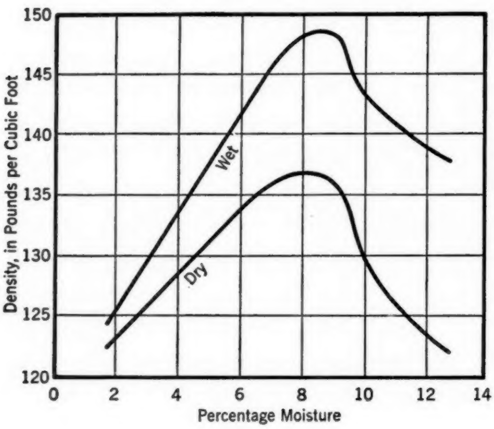

Fig. 1.—Proctor Analysis of Test Soil

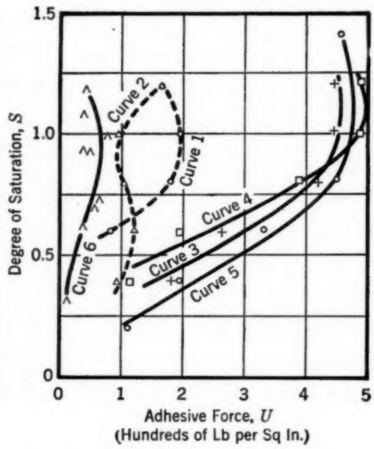

Fig. 2.—Adhesive Force of Various Soils

The tests were conducted with $1\frac{1}{4}$-in. standard steel pipe, ranging in length from 6 in. to 24 in., imbedded in a local sand-silt having characteristics as shown in Fig. 1. The sieve analysis by weight was as follows:

Sieve number	Percentage finer
1 in.	98.3
$\frac{3}{4}$ in.	95.6
$\frac{3}{8}$ in.	89.3
No. 4	85.4
No. 10	80.0
No. 40	65.5
No. 100	56.1
No. 200	53.1

The test apparatus consisted of a 1-cu yd wood box containing the test pile and soil. A hydraulic jack with dial gauge was used to apply uplift loads and was

mounted on a cross girder that transferred the jack reactions into the box frame. Temperatures of the soil and of points along the test pile were measured by recording thermocouples. A total of 15 tests were run, covering various combinations of density, moisture content, and pile length.

Test Results.—Fig. 2 gives the adhesive force of various soils to wet wood for varying degrees of saturation. It compares the results of experiments conducted in Russia[2] (curves 1 to 5) with experimental results of the tests described in this paper (curve 6). The characteristics of the soils tested are tabulated as follows:

Curve number (Fig. 1)	Type of soil	Temperature of test (degrees Fahrenheit)
1	Clayey	29–30
2	Silty	29–30
3	Clayey	11–15
4	Silty	11–15
5	Sandy Loam	11–15
6	Sand–Silt	18–25

Comparison of the Russian data with the test results indicates that, although the general trends of behavior appear similar, the test results appear to yield much lower values than would be expected as a result of the differences between wood, concrete, and steel. Unfortunately, insufficient data were available on the Russian tests to permit comparison of soil types, optimum moistures and densities, and other important test factors.

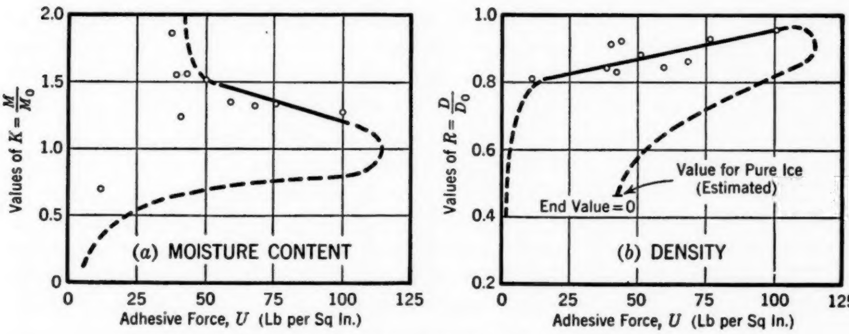

FIG. 3.—EFFECT OF VARIOUS FACTORS ON THE ADHESIVE FORCE

It is interesting to note that for all soils there appears to be a reversal of curvature at a saturation amount of approximately 1.0. It can be expected that all curves will become asymptotic to the value of pure ice as the saturation increases. On the dry side it can be anticipated that all soils will approach a minimum value at zero moisture content that will result from the pure mechanical grain friction of the soil in its loosest state. This point is probably very close to zero for all soil types.

[2] "The Force of Congelation of Frozen Grounds with Timber and Concrete," by I. S. Vologdina, *SOPS and KIVM*, Academy of Sciences, Vol. II (1936).

The variation of the force of adhesion with soil density and moisture content is given in Fig. 3. The curve of values of u versus the ratio of observed moisture content M, to optimum moisture content M_0, is shown in Fig. 3(*a*). The variation of values of u with the ratio of observed density, D, to density at optimum moisture content is plotted in Fig. 3(*b*).

An interesting feature of the tests was the high refreezing strengths developed. After the test had been carried to failure, the load was removed for a period of 1 to 2 min. The pile was then rapidly loaded. It was found that values of up to $\frac{1}{2}$ to $\frac{2}{3}$ u were developed before failure again took place.

Working Value of Adhesive Force.—After considerable study of all available data it was decided that a value of $u = 20$ lb per sq in. could be used as a safe equivalent of the adhesive force u for steel piles in all soils except those with a natural density less than 85% of optimum or with a moisture content of less than 80% of optimum. This excludes highly organic soils and very dry soils such as well-drained sand or gravel terraces.

The value of u was further qualified for the design under consideration by the following criteria: (1) The minimum imbedment of a pile below the permafrost table will be 20 ft; and (2) no joint or coupling will be permitted less than 5 ft below the permafrost table.

Design of Tower Foundation

Structural Arrangements.—Fig. 4 shows the type of design finally adopted. The tower loadings are transferred through the bolt system and annular rings into a set of 6 radial spider beams that are supported on 8-in. double extra strength, steel pipe piles. Peripheral horizontal bracing was designed to distribute the horizontal shear to all piles and to provide added lateral rigidity to the structure. The principle of the design was to eliminate as much field welding as possible and to provide a structure that could be assembled easily in the field. The design is intended for use with piles either drilled in or driven into locally thawed zones. The former method, of course, is to be preferred since it ensures greater accuracy in positioning the piles.

Reduction of Heat Transmission.—The structural analysis presented no unusual applications of established theory. The heat transmission problem, however, is of interest because of its complexity and the method used to resolve it. The factors that influence the amount of heat flowing down into the permafrost are the mass of the tower, the ambient temperature, the intensity of radiation, the emissivity of the tower, the effect of winds, the temperature and thermal conductivity of the permafrost, and the specific resistance of the path of flow.

It is obvious that the critical period in the design of the structure occurs during the months of July and August when the temperatures are highest and maximum sunlight prevails. During this season, fortunately, the probability of occurrence of winds on the order of design magnitude (100–150 miles per hr) is very low.

An attempt was first made to establish standard daily curves, or reliable average values, for factors such as temperature, radiation, and emissivity. Available data were insufficient to permit establishment of a reliable daily

curve. This problem in variable flow was reduced, therefore, to one of steady flow by assuming the tower above the insulators as a mass of constant temperature. For the purposes intended, a temperature of 80°F was chosen as being amply conservative.

The other end condition to be fixed was the temperature of the permafrost. Observations by the Corps of Engineers, United States Army, indicated that for depths of permafrost up to about 25 ft the average summer temperature could be expected to be about 1° to 2° below freezing. Therefore the temperature for the bottom of the pile was chosen as 30° F.

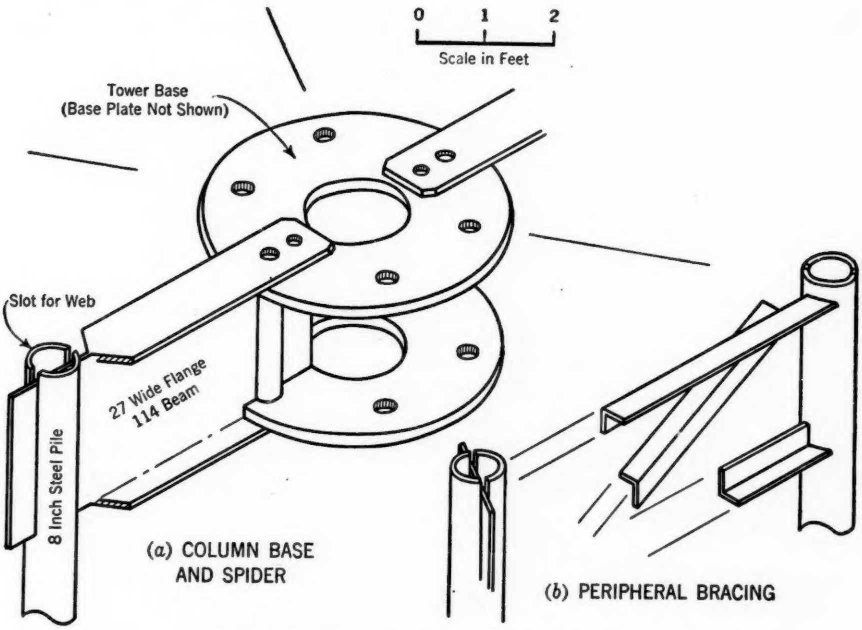

FIG. 4.—STEEL ASSEMBLY FOR TOWER FOUNDATION

The method of analysis involved the following steps: (*a*) Determination of the quantity of heat flowing down each pile; (*b*) determination of the permissible rate of heat flow; (*c*) determination of the heat flow through a heat diverter; (*d*) determination of the size of diverter; and (*e*) determination of the required pile length.

a. The total quantity of the heat that can flow down each pile.—The equation for steady heat flow was used for this determination.

$$Q_T = \frac{\Delta_T}{\dfrac{x_1}{k_1 A_1} + \dfrac{x_2}{k_2 A_2} + \dfrac{x_3}{K_3 A_3} \cdots \dfrac{x_n}{k_n A_n}} \qquad (1)$$

in which Q_T is the total heat flow in British Thermal Units (BTU) per hour; Δ_T is the difference in temperature between ends of system in degrees Fahren-

heit; X is the length of particular section of path in feet; k is the thermal conductivity of a section in BTU per square foot per hour, per foot per degree Fahrenheit; and A is the mean cross-sectional area of a section in square feet. The subscripts 1, 2, 3 ... n identify the number of sections in the total path.

b. The maximum permissible rate of heat flow down the pile.—This flow was assumed to be a rate that would melt out an annular layer around the pile of 0.05-in. thickness at a rate not to exceed 1 ft vertically in 24 hr. The value of 0.05 in. was based upon the soil used in the tests; and for any soil, the thickness of the annular layer was fixed as the size at which 85% was finer. Making an assumption as to the moisture content and density, this item resolved into a simple calculation of the heat required to melt the moisture, assuming the pile

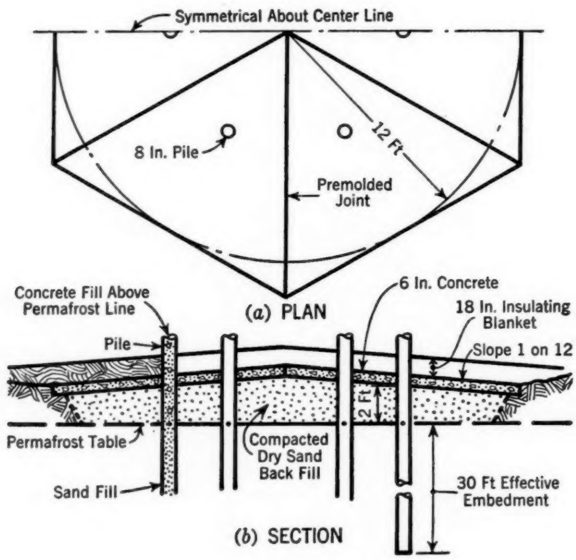

Fig. 5.—Heat Diverter Pad

and surrounding soil to be 32° F. If the value of the heat flow determined in step a exceeds the permissible value, some means is necessary to keep the excess heat from flowing down the pile. A number of methods might be suggested, such as baffles or artificial cooling. For the structure in question it was decided to try a concrete pad buried under an insulating blanket and designed to spread heat in a lateral direction and then down into the permafrost. This pad is illustrated in Fig. 5.

c. Heat flow through diverter.—The point of diversion is first picked. In this case the point was on the pile 2.75 ft above the assumed permafrost table. Knowing the permisssible rate of flow and the temperature of the bottom of the pile, the temperature at the point of diversion is calculated by a simple application of the basic equation for heat flow. If the subscript p is used to denote

permissible flow through the pile:

$$\Delta T_p = \frac{Q_p X_p}{k_p A_p} \quad (2a)$$

or

$$\Delta T_p = Q R_p \quad (2b)$$

in which $R_p = \frac{X_p}{k_p A_p}$ may be defined as the total resistance of the system or path. Since the temperature at the point of diversion, T_p, cannot exceed $30° + \Delta T_p$ the quantity of heat to be handled by the diverter can be determined. The value of R of the pile, R_p, is deducted from the total system value, R, that is computed from step a. The total heat flow in the system, Q_T, is then

$$Q_T = \frac{T_t - T_D}{R - R_p} \quad (3)$$

in which T_t is the temperature of the tower; then

$$Q_T - Q_p = Q_D \quad (4)$$

in which Q_D is the quantity of heat to be handled by the diverter. For the particular example analyzed, this quantity amounted to $1.90 - 0.45 = 1.45$ BTU per hr.

d. Diverter size.—It was assumed that only one half of the circumferential area around each pile would be effective in dissipating heat. The action of the diverter may be likened to flow through a pipe having an ever-increasing cross-sectional area (the concrete pad) and having an infinite number of infinitesimal side outlet pipes (the soil above the permafrost table) discharging into a reservoir of fixed elevation (the permafrost).

The first step is to adopt a trial size. A radius is assumed, and the effect on melting the permafrost is checked by determining the time required to melt an inch of depth using the formula:

$$\frac{t = A\ d\ M\ D\ 144}{12\ Q_D} \quad (5)$$

in which A is the horizontal area of permafrost under the diverter; d is the depth of layer (in this case 1 in.); M is the moisture content of soil by weight as a decimal; D is the density; t is the time in hours; and Q_D is the flow through the diverter in BTU per hour. In practice it will be found that almost any reasonable size of diverter will keep the rate of melting within safe limits. For the case in question a radius of 6 ft resulted in a rate of melting of 1 in. in about 55 days. It should be noted that the limit of 1 in. is arbitrary and could be established at other values depending upon the designer's judgment. The value of t should be equal to the length of the thawing (summer) season.

The thickness of concrete must be selected next. In this case a thickness of 6 in. was selected for economy. The relationship of heat flow in the soil and concrete warrant keeping this thickness as small as practicable.

It is evident from an inspection of the problem that, for any small finite interval of radius

$$Q_2 = Q_1 - Q_s \quad (6)$$

in which Q_1 and Q_2 are flow in the concrete pad, and Q_s is the flow through an incremental soil cylinder. The relationships are indicated in Fig. 6. It should be noted that the conditions indicated are not completely correct physically because the elevation of the permafrost table should rise a certain amount. The assumptions implied, however, are considered to be on the side of safety.

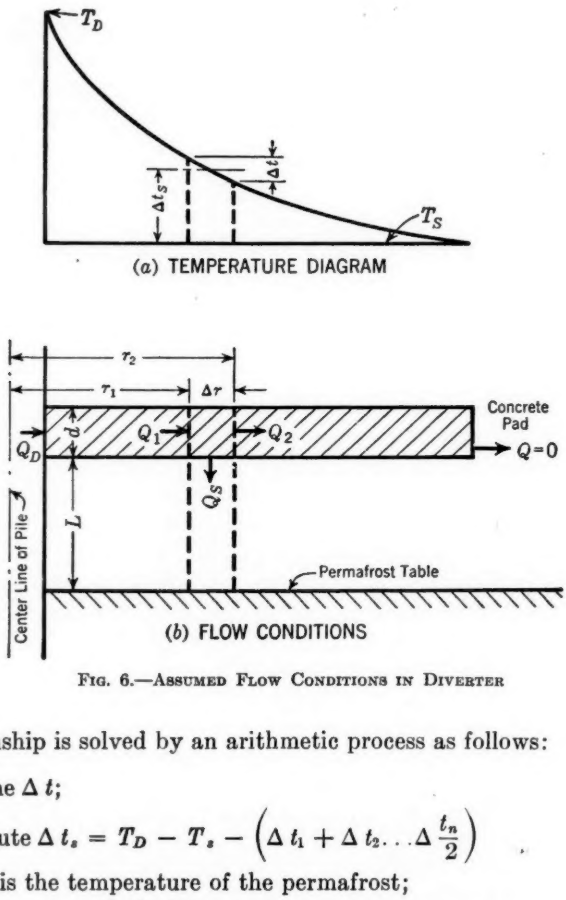

FIG. 6.—ASSUMED FLOW CONDITIONS IN DIVERTER

This relationship is solved by an arithmetic process as follows:

1. Assume Δt;
2. Compute $\Delta t_s = T_D - T_s - \left(\Delta t_1 + \Delta t_2 \ldots \Delta \frac{t_n}{2}\right)$

in which T_s is the temperature of the permafrost;

3. Compute $Q_s = \frac{k_s A_s \Delta t_s}{L}$ in which $A_s = \frac{\pi}{2}(r^2{}_2 - r^2{}_1)$

and the Q_s is the average heat flow in the annular soil ring;

4. Then $Q_1 - Q_s = Q_2$;
5. Compute Q_{ave} as a check against $\frac{Q_1 + Q_2}{2}$ from step 4 above: Q_{ave}

$\frac{k_c A_s \Delta t}{\Delta r}$ in which A_c = log mean area; and

6. Revise the assumption for Δt as indicated by the result of step 5.

At the end of the process the final flow in the pad should be zero and the allowable total temperature drop ($\Sigma \Delta t$) completely consumed. If residual flow still exists in the concrete, the thickness or the radius must be increased or both. The computation, once set up, can be solved fairly rapidly for a number of combinations of r and d.

It was noted for the case in question that the critical region for the diverter lay in radii of less than about 2 ft. In this zone the soil cylinder is capable of diverting very little heat flow, and excessive thickness of concrete would be required. To eliminate this an annular sheet copper element was employed, extending to an average radius of 3 ft. The step calculations outlined are readily adapted to include provision for the copper element, assuming (for simplicity) that all the flow in the pad is taken by the copper. In general it would appear economical to keep the concrete thickness to a minimum consistent with other requirements, and in the critical region close to the pile to attain the required heat transmission with a high conductivity metal. The calculations indicated that less than $\frac{1}{8}$-in. thickness of copper was required. This was arbitrarily increased to 5/16 in. for structural reasons.

Fig. 5 shows the type of element and pad adopted for the design in question. Particular pains have been taken to prevent infiltration of moisture for two reasons:

a. To reduce the possibility of galvanic corrosion; and
b. To prevent feeding of heat to the pile due to subsurface flow.

e. Required length of pile.—The following criteria were set up:

For winter conditions with the pile completely frozen in, the allowable value of skin frictional resistance (u) was taken as 20 lb per sq in. of pile surface. The minimum length of effective imbedment in permafrost is 20 ft, and the highest pile joint was taken to be at least 5 ft in permafrost.

For summer conditions when the pile may be all or partly frozen in, the minimum pile imbedment was assumed to be 30 ft based on an allowable rate of melting of 1 ft per day for 30 consecutive days. The pile, when completely unfrozen, should develop sufficient skin friction to resist forces due to a 60-mile per hr wind. Effective imbedment specifies that all layers of highly organic materials, ice lenses, and other impurities, according to the judgment of the designer, should be excluded from contributing to the pile resistance. The criterion for minimum imbedment under summer conditions is based upon the assumption that 30 consecutive days is the maximum period under which the design temperature conditions can be expected to prevail. This was based on examination of temperature records for a number of locations in the Arctic and may be adjusted for any specific locality in which reliable information is available.

Summary

The method of design presented above is admittedly no more than a crude approach to a method that will become more accurate commensurate with an increase of knowledge in the basic factors, such as temperature regimens, radiation, and soon, an increasing knowledge of permafrost mechanics. How-

ever, it is recommended to the readers' attention because it indicates that the question of heat transmission may be important even on unheated structures; and it provides a method of attack that can be employed for any structure founded on piles. It also recognizes certain important factors that affect the success of the foundation and provides the framework within which they can be bracketed.

Acknowledgment

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